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AN INTRODUCTION TO THE LITERATURE OF SEARCH THEORY

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INTRODUCTION

The purpose of this paper is to survey the one-sided search problem, starting with Koopman's work in 1946 and continuing to the present. The paper summarizes some basic results for both the optimal allocation of effort problem and the best track problem for stationary and moving targets; but, it is intended as an introduction to the literature of the field rather than an exposition of it.

The paper does not include two-sided searches, i.e., searches in which the target reacts in any intelligent way to the searcher. It does not include surveillance problems or problems involving false contacts or decoys. It includes only repeatable searches.

This survey was aided by earlier surveys, particularly J. M. Dobbie's published in Operations Research in 1968, and Marc Mangle's 1980 OEG publication. The bibliography includes not only those papers actually referenced in the present work, but also other papers of interest in the area of search.

THE SEARCH PROBLEM

Search theory is one of the oldest areas of operations research. Problems involving search arise in such diverse areas as the military looking for enemy submarines, the Coast Guard searching for small boats lost in a storm, prospectors surveying for mineral deposits, the forest service looking for missing backpackers, law enforcement officers searching for lost weapons or escaped criminals, a secretary looking for a missing file, or an analyst scanning a computer printout for a particular piece of data. All of these problems have two elements in common -- a target, in the broad sense of something being searched for, and a searcher.

There are usually two types of cost involved in search problems. The first, the cost of the search itself, may be measured in such terms as dollars, time, manpower expended, or fuel expended. We often want to search in such a way as to maximize the probability of finding the target at a minimum cost, or until our resources run out (fixed cost). A second cost is the cost of not finding the target. This cost may be measured in dollars, in inconvenience, or even in lives lost. The two costs need to be balanced in each search situation. In general, we want to devise a search plan, or "track" which uses the resources most effectively under such

physical limitations as the terrain, the searchers, the instruments used, the resources available, and the nature of the target itself.

The search problem can be loosely described as follows:

- The target is located in an area which is much too large for the searchers to search completely.

- The location of the target is not known exactly, but probabilities can be associated with subregions of the main search area.

- The target may (or may not) move.

- One or more searchers may look for the target, and they may use detection equipment to do so.

In order to solve the problem, we need:

- A model for the location of the target at the start of the search. This model we will call the initial density.

- A model for the motion of the target, which we denote by $q(x,y,t)$.

- A mathematical goal, or objective function, such as minimizing the time to find the target, or maximizing the probability of detection by time T.

The search literature breaks the problem down into two main categories: optimal allocation of effort problems, and best track problems. The optimal allocation of effort problem is mathematically the easier of the two problems and hence more work was done in this area earlier. Optimal allocation of search effort may mean, for example, optimizing the amount of time spent searching in each subarea. These problems are nice mathematically since it is often possible to prove that a plan is optimal. However, it may be that the optimal plan is not "doable." For example, in the figure below, the plan may say to put 50 percent of the total effort in (3,2) and 50 percent in (3,4). Due to physical constraints, this allocation may be impossible,

	1	2	3	4
1				
2				
3		.50		.50
4				

e.g., the searcher may not be able to get from (3,2) to (3,4) without expending some effort in (3,3). It would be more useful for the searcher to have a track to follow. But the best track

problems are difficult to solve. Work has progressed significantly only since the mid-seventies.

We will look first at the best allocation of effort problem and its history.

KOOPMAN, 1946

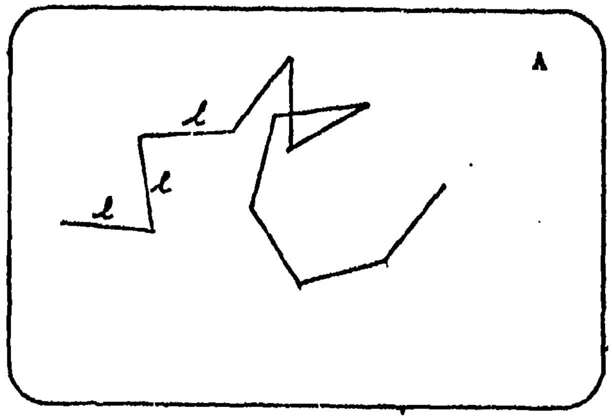
The earliest developments in search were made by Bernard Koopman and his colleagues in the Anti-Submarine Warfare Operations Research Group (which later became the Operations Evaluation Group) of the U.S. Navy during World War II. Their purpose was to aid the Navy in finding efficient ways to search for enemy submarines. The work done from 1942 to 1945 was published in a book, Search and Screening (Koopman, 1946). Originally classified Confidential, the work was declassified in 1958. A new edition of Search and Screening was published in 1980. Many of the results from the OEG work were published in a series of articles in Operations Research in the mid-fifties (Koopman, 1956 a&b, 1957). Koopman's work is basic to search theory and is a good place to start a survey of this field.

Let us look first at the law of random search[1]. Suppose there is a region, A, over which a search must be made. Assume nothing is known about the location of the target except that it is in A, i.e., we will assume a uniform target distribution and that the target is stationary relative to the searcher. Assume that if we

---

[1] See Koopman (1946), p.28 or Koopman (1980), p. 71.

pass within W/2 distance units from the target, we will detect it with probability 1. Assume also that the searcher takes a random piece-wise linear path of total length L, and $\ell = L/n$ is the length of one of n equal, rather long (in relation to W) segments.



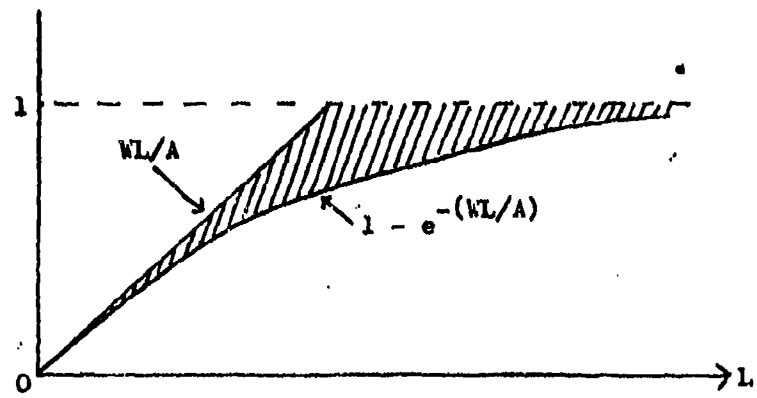
Koopman shows that the probability of finding the target under these conditions is

$$P = 1 - e^{-(WL/A)}.$$

Since the search path was random, this probability is usually lower than it would be if we had searched systematically. P is then a lower bound for the actual probability of detection and is useful for approximation purposes. If we assume that it is only necessary to search in a straight line path, P becomes

$$P = WL/A.$$

This estimate of P assumes "ideal" conditions and thus provides an upper bound for the probability, as indicated in the figure below.



The true probability lies somewhere in the hatched region.

Koopman looked at the optimal allocation of effort problem in both discrete and continuous space. His objective was to optimize allocation of search effort. Suppose that we have a search area divided into two parts A_1 and A_2[1]. Suppose that the probability that the target is in A_i is p_i, $i = 1,2$, and define ϕ_i, the density of search effort in A_i, by

$$\phi_i = \frac{\text{Effort in } A_i}{A_i}$$

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[1]See Koopman (1946) p. 35, or Koopman (1980) p. 146.

Koopman found that, assuming the target is stationary (or more generally, stationary relative to the searcher) and assuming the law of random search, one of three situations arises:

If P_1/A_1 is much larger than P_2/A_2, search only A_1.

If P_2/A_2 is much larger than P_1/A_1, search only A_2.

Otherwise, distribute the total effort $\Phi = A_1\phi_1 + A_2\phi_2$ using $\phi_i = \log(P_i/A_i) - (1/A)[A_1\log(P_1/A_1) + A_2\log(P_2/A_2)] + \Phi/A$.

For the continuous case, Koopman defined the problem as follows:

- The target is stationary.

- It is contained in a region A. The probability before the search starts that the target is in (x,x+dx) and (y,y+dy) is p(x,y)dxdy.

- The total search effort is Φ.

$\phi(\ )$ is the density of search as a function of x. If we integrate $\phi(\ )$ over any subregion B of A, we get the effort expended in B. Koopman shows that the problem reduces to maximizing

$$P(\Phi) = \iint_A p(x,y)(1 - e^{-\phi(x,y)})dxdy$$

where $p(x,y)$ is the probability that the target is around (x,y) and $1 - e^{-\phi(x,y)}$ is the probability of finding it there assuming random search. Using Lagrange multiplier and Calculus of Variations techniques, he finds the unique b such that

$$\log(b) - (1/A_b)\iint_{A_b}\log p(x,y)\, dxdy + \Phi/A_b = 0$$

where A_b is a subset of A which depends on b. Then $\phi(x,y) = \log[p(x,y)/b]$ is the function defined by $\iint_A \phi(x,y)dxdy = WL = \Phi$ and $(x,y) \geqq 0$ which gives $P(\phi)$ its largest value. Geometrically, we can find this value of b by first plotting $z = \log p(x,y)$ over the region A. Cut this surface by the horizontal plane $z = \log b$ in such a way that the volume of the surfaces above the plane is equal to Φ. The orthogonal projection on the x,y plane will be A_b.

For both the discrete and continuous cases, Koopman observed that for this problem effort allocation has an additive property. That is, if Φ units of effort are available at the beginning of the search and Φ' more units become available later, the best search plan remains the one which would have been chosen at the beginning

had we known the total effort would be $\Phi + \Phi'$. In other words, says Koopman

> "A well planned search cannot be improved by a redistribution of search made at an intermediate stage of the operation in an attempt to make use of the fact that up to that time the target had not yet been observed."[1]

[1]Koopman (1946), p.38 or Koopman (1980), p.151.

SUBSEQUENT DEVELOPMENTS

Variations on both of Koopman's problems followed quickly after the publication of the unclassified version of his work. The discrete case easily extends to n boxes and to many variations.

Blachman (1959) looked at the problem of finding an object in one of n boxes. He assumed that the probability the object appears in each box is known, and the time of appearance is uniformly distributed over a large interval. Blachman and Proschan (1959) derive an optimum search procedure for a generalization of Blachman's problem. In this case, the object's arrival is in accordance with a Poisson process with arrival rate A. A cost of looking in each box is added. They consider which boxes to scan and how to schedule the scans to minimize the time between the arrival of the object, and finding it. The model is applicable to, say, the appearance of missiles for which early detection is crucial.

Gilbert (1959) added to Koopman's two cell search a cost (perhaps in time) for switching from one cell to another. He treats the problem as a kind of one person game, and applies the method to a search for an odd sized bolt in one of two bins. Gluss (1961) looked at the n-box problem if the boxes are all in a line and Ross

(1968) added a reward R_i for finding the target in box i. Wegner (1980) find necessary and sufficient conditions for the existence of admissible search strategies which minimize the expected cost of "at least surely" finding an object when overlook probabilities are included. He gives a procedure for computing an optimal strategy.

Most of the above problems were solved by a dynamic programming approach. Matula (1964) derived conditions for the existence of an ultimately periodic search with minimum cost. He finds a closed form solution to this problem rather than the recursive solution of dynamic programming. Pollock (1964) introduced a Bayesian approach to the optimal allocation problem. Decisions are made sequentially based on what had been observed until that time to minimize the expected cost of searching and making wrong decisions. In 1970, Pollock (1970) considered the case when the target is moving between two regions. The target moves in a Markovian fashion and with known parameters. He tries to find the expected number of "looks" required to find the target, and solves the problem in certain special cases by means of dynamic programming.

The preceeding papers all deal with the problem of effort allocation when the search space is discrete. The following papers use continuous search space, or both continuous and discrete space through the use of the Stieltjes integral. Most of the recent papers use this latter approach.

Charnes and Cooper (1958) showed that mathematical programming could be used in search problems to look at broader classes of problems. They applied convex-programming along with the Kuhn-Tucker conditions to obtain the solution. The algorithm they obtained was an important step in solving search problems by computer.

In 1961, deGuenin generalized Koopman's models in an algorithm which made no assumptions on the detection probability function. He felt that the law of random search (negative exponential) is not valid for many non-military applications. He used instead functions he terms as "regular" -- that is, the graph is strictly concave downward, passes through the origin with a tangent of positive slope, and increases monotonically to a horizontal asympotote no higher than positive one. Many detection functions used by Koopman have this property, and most subsequent mathematical developments have been based on deGuenin's regular functions.

Dobbie (1963) started with the additive property mentioned by Koopman and used this property to derive the optimal search distributions. He was the first to define passive observations -- the target does not react to the search, the search does not materially change the target (as covering a lost item with dirt) or the searcher (as with fatigue) -- as opposed to active observations and to discuss the mathematical consequences. He pointed out that often, especially with active observations, the detection function is not regular (or deGuenin).

Zahl (1963) derived necessary and sufficient conditions for the existance of solutions to the problem of maximizing the detection probability with a given effort.

Various sequential formulations of the search problem have been applied to several fields. Engel (1957) looked at the search for certain minerals as a two stage process. The first, and least expensive, consists of one or more preliminary searches. The second search is detailed and more expensive, and occurs only where the required "clusters" of signals in the preliminary search indicate the target is likely to be found. Posner (1963) uses a similar preliminary scanning technique to search for a lost satellite by radar. DeGuenin (1963) adds a middle stage, screening the data, when searching for oil wells.

Stone made use of Calculus of Variations, convexity properties, and generalized Lagrange multiplier techniques (which allow for inequality constraints and do not require differentiability assumptions) to formulate a systematic treatment of search theory in his 1975 book <u>Theory of Optimal Search</u>. In this book he deals primarily with stationary targets but extends his methods to false targets and Markovian motion.

Conditionally deterministic target motion -- motion in which the initial position and speed of the target is known but its direction is not -- was considered by Stone (1973) and Pursiheimo (1977).

Mangle (1980) included an algorithm for Markovian target motion in which the moving target motion is reduced to a sequence of stationary target problems. The observation that a search plan maximizes the overall probability of detecting a moving target if and only if it maximizes the probability of detecting a stationary target at discrete time intervals was made by Brown (1980). When there is random target motion, the number of possible target paths is infinite. Stone (1979) worked on this problem. When the detection function is concave, he gave conditions for optimal search plans which include any "reasonable" target motion.

Stone, et. al. (1978) summarizes the optimal allocation problem and included several algorithms for its solution. They found necessary and sufficient conditions for optimal search for a moving target when time is discrete and an exponential detection function is assumed.

> For a search for a moving target to be optimal, it is necessary and sufficient that at each time t it assigns an allocation which is optimal for the stationary target problem which one obtains at time t by conditioning on failure to detection after t as well as before t under the plan.[1]

The algorithms first find an optimal allocation of effort for the initial target distribution. Then for times t = 2,...,T, they

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[1]Stone, et. al. (1978), abstract.

calculate the posterior distribution for the target location at time t given failure to detect at all previous times and allocate effort for that stationary target problem. The plan resulting from the first pass is called the "myopic" plan. Subsequent passes are made reallocating the effort each time. One can come as close to the optimal plan as desired by performing enough passes. In many situations, the myopic plans are almost as good as the optimal plan.

> The optimal plans typically pay a penalty in probability of detection at the early hours in order to maximize that probability at time t. ...when the myopic plan is close to optimal, the myopic plan is a good one for operational purposes.[1]

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[1]Stone, et. al. (1978), abstract.

KOOPMAN REVISITED

In 1979, Koopman (1979, a&b) published two papers, and in 1980 republished his 1946 work, <u>Search and Screening</u>. In 1979a he generalized his 1946 work. In 1979b his emphasis was on operational feasibility; this subject will be discussed in the last section of this paper. Both of these papers are incorporated in the 1980 edition of <u>Search and Screening</u>.

Koopman rederived his law of random search under slightly more general assumptions. He assumed:

- Search is by passive observations.
- The search is repeatable.
- Short range detectors are used.
- All factors (target, searcher, and environment) are constant.
- $\phi(x,y)$ is the search effort applied at (x,y).

Define $D(x,y,z)$, where $z = \phi(x,y)$, as the probability the target is detected given that it is at (x,y) and with search effort z. Then

$$D(x,y,z) = 1 - e^{-w(x,y)z}, \quad w(x,y) \geq 0$$

In general, the larger $w(x,y)$, the greater the probability of detection; it is a sort of local measure of detectability at (x,y). Under the assumption that everything within a range R of the searcher is detected, w becomes the sweepwidth defined in Koopman's 1946 paper.

The optimal distribution of searching effort problem can be formulated as follows.

Find the search density function $\phi(x,y)$ which maximizes

$$P(\phi) = \iint_A p(x,y)D(x,y,\phi(x,y))\,dxdy$$

$$= \iint_A p(x,y) \left\{1 - \exp[-w(x,y)\phi(x,y)]\right\} dxdy$$

subject to $\iint_A \phi(x,y)dxdy = \Phi$, and $\phi(x,y) \geq 0$.

Φ is the total available effort.

He assumed further that the functions p, w, and ϕ are all continuous. He used a method developed by Gibbs in 1928 to solve this Calculus of Variations problem. Koopman shows that there is a unique λ (similar to the "b" in his earlier work) such that the optimal $\phi(x,y)$ is

$$\phi(x,y) = [1/w(x,y)] \log [p(x,y)w(x,y)/\lambda] \quad \text{for } (x,y) \in A(\phi),$$

and

$$\Phi = \iint_{A(\phi)} \left\{ \log[p(x,y)w(x,y)] - \log \lambda \right\} dxdy/w(x,y).$$

The geometric interpretation is the same as in the earlier formulation.

By replacing the exponential detection function $D(x,y,z)$ with a partial detection function $b(x,y,z)$, where

$$b(x,y,z) = 1 - \int_0^\infty e^{-wz} dG(w)$$

(the integral is a Laplace-Stieltjes transform), Koopman finds a larger class than the regular (deGuenin) detection functions for which his results are valid. $G(w)$ usually involves (x,y); as w goes from 0 to ∞, $G(w)$ goes non-decreasingly from 0 to 1. (For other properties of G see Koopman (1979a)). However, Koopman points out that "The practical problem of finding $G(w)$

has so far only been solved by guesswork, without subsequent verification."[1] The Normal distribution has been suggested. Stone (1975), and Richardson and Belkin (1972), have studied the use of the gamma distribution when the sweep width is uncertain.

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[1]Koopman (1979b), p.538.

BEST TRACK PROBLEMS

Optimal effort allocation problems are relatively easy to solve; however, it is common that the goal is to find the best search track. Mathematically this is a harder problem, and often approximate solutions are all that are available.

In 1946, Koopman developed the method of parallel sweeps for searching for a stationary target or a target whose speed and direction are known. In either case it is assumed that the prior target distribution is uniform in the search area. This search plan calls for the searchers (e.g., airplanes) to move along a series of parallel lines (whose distance apart depends on the search environment) which cover the area. In the case of a moving target, the sweeps are made parallel to the target's motion.

Between the 1940s and 1970 almost no progress was made in solving best track problems. In 1974, Lukka (1974) worked out the theory of optimal track for stationary targets, targets whose motion is known, and targets whose motion is almost known. The methods rely on the theory of optimal control. Mangel and Thomas (1979) wrote a tutorial type paper developing from first principals analytical methods for search for a moving target.

Mangel (1981), basing his work on Lukka's, derived algorithms for the optimal control result, one where the detection rate is independent of velocity and one where it is not. Mangel defines $f(x,t,z)$ and $u(x,t,z)$ as

$$f(x,t,z)dx = \text{Prob}[x(t) \in (x,x+dx) \text{ and search along } z(\tau),\ 0 \leq \tau \leq t \text{ was not successful}]$$

$$u(x,t,z) = \text{Prob}[\text{non-detection to time } T \mid x(t) = x, \text{ and search along } z(\tau),\ t \leq \tau \leq T]$$

He showed (Mangel and Thomas, 1979) that these quantities must satisfy

$$\frac{\partial f}{\partial t} = \sum_{i,j} 1/2 \frac{\partial^2}{\partial x_i \partial x_j}(a_{ij} f) - \sum_i \frac{\partial}{\partial x_i}(b_i f) - \psi(x,t,z) f \tag{1}$$

with $f(x,0,z) = f_0(x)$ plus boundary conditions,

$$\frac{\partial u}{\partial t} = - \sum_{ij} 1/2 a_{ij} \frac{\partial^2 u}{\partial x_i \partial x_j} - \sum_i b_i \frac{\partial u}{\partial x_i} + \psi(x,t,z) u \tag{2}$$

with $u(x,T,z) = 1$ + boundary conditions,

where a_{ij} is the diffusion matrix and $b_i(x)$ represents the average velocity of the target (the drift coefficient). $\psi(x,t,z)$ is the instantaneous detection rate, defined by

$$\psi(x,t,z)dt = \text{Prob}[\text{detection in } (t,t+dt) \mid X(t) = x, \; Z(t) = z, \text{ no detections before } t]$$

Mangel modified the ray techniques of J.B. Keller (Keller, 1978) to solve equations (1) and (2).

To find the best search track which maximizes $P(t)$, the probability of detection at time T, we must pick $v(t)$, the searcher velocity so that $P(T) = 1 - \int f(x,T,z)dx$ is maximized, $dz/dt = v(t)$, $z(0) = z_0$, and $f(x,T,z)$ satisfies (1). Lukka (1974) derived the maximum principle for this problem, showing that the optimal velocity $v^*(t)$ makes $H(t,v,A)$ a maximum over all allowed velocities, where $f(x,t,z)$ satisfies (1), $u(x,t,z)$ satisfies (2), $dz/dt = v(t)$, and

$$H(t,v,A) = \int f(x,t,z)u(x,t,z)\psi(x,t,z)dx + \Sigma A_i(t)v_i(t),$$

$$dA_i/dt = -\int f(x,t,z)u(x,t,z)\frac{\partial\psi}{\partial z_i}(x,t,z)\, dx, \text{ with } A(T) = 0.$$

Mangel points out that when the detection function is independent of velocity, the searcher should move at maximum speed and in the direction of $A(X)$ where

$$A(t) = A(0) - \int_0^t\!\!\int f(x,s,z)u(x,s,z)\psi dxds.$$

$$A(0) = \iint_0^T f(x,t,z)u(x,t,z)\psi dxdt.$$

It seems clear that we are a long way from the routine solution of problems of this sort.

OPERATIONAL IMPLEMENTATION

In his "Operational Critique of Detection Laws," Koopman asks, "Given a theoretically perfect solution to a problem of optimal search, how accurately can it be implemented by the dispositions of paths of real searchers?"[1] His 1946 work looked at this question for several situations and decided that between 70 and 85 percent of the theoretical optimum is the best which can be expected. Since this is the case, he pointed out that it may be better to spend time finding "good enough" solutions, i.e., finding good "useful first approximations" rather than continuing to find elegant exact solutions.

Many of the techniques discussed in this paper require extensive computer time to implement. A solution which requires an hour on a larger computer is not very useful for searchers operating from an aircraft carrier or from a small law enforcement office. The searchers need to know in real time where to look and how long to look there. In order to make the theory more accessible to those who need it, much work is needed to devise good, simple approximations to optimal plans.

[1] Koopman (1979a), p.131.

The analyst also needs to let the searcher know how much the plan depends on the search path being followed exactly, since some plans are less flexible in this regard than others. If the probability of detection does not depend strongly on the plan, other operational factors can be considered by the searchers.

Koopman emphasizes the idea that any mathematical model should have a solid basis in reality, be as simple as possible while still describing the problem, and the results should be operationally implementable. He says, "...we may be guided by the following general principle:

> OCCAM's(OR) RAZOR: Complications in models are not to be multiplied beyond the necessity of practical application and insight.[1]

[1]Koopman (1979a), p.131.

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